

Chapter 1. Resilience of Large Scale Resource Systems

L.H. Gunderson¹, C.S. Holling², L. Pritchard¹ and G.D. Peterson³

¹Dept. of Environmental Studies, Emory University, Atlanta, GA, USA

²Dept. of Zoology, University of Florida, Gainesville, FL, USA

³Center for Limnology, University of Wisconsin, Madison, WI, USA

1.1 Introduction

Regional scale systems of people and nature provide some of the most vexing challenges for attaining social goals of sustainability, biological conservation or economic development. There are many more examples of failures than successes, as measured by numerous resource systems that exist in a constant or recurring state of crisis (Ludwig et al. 1993). In the Florida Everglades, agricultural interests, environmentalists, and urban residents contest with one another for control over clean water (Light et al. 1995). In the USA's Pacific Northwest, various advocates of salmon argue over the appropriate use of the Columbia River with those who prefer cheap hydroelectric power (Lee 1993, Volkmann and McConaha 1993). The nations surrounding the Baltic Sea struggle with issues of governance as the fish populations and water quality of the sea declines (Jansson and Velner, 1995). Within Zimbabwe, large-scale land use conversions are testing stabilities of both ecological and political structures. In these cases resource management has taken a pathological form in which the complexity of the issues, institutional inertia and uncertainty lead to a state of institutional gridlock, when inaction causes ecological issues to be ignored, and existing policies and relationships to be continued.

Paradoxically, this failure arises from the success of initial management actions. Managers of natural resource systems are often successful at rapidly achieving a set of narrowly defined goals. Unfortunately, this success encourages people to build up a dependence upon its continuation, while simultaneously eroding away the ecological support that it requires. This leads to a state in which ecological change is increasingly undesirable to the people dependent upon the natural resource, and more difficult to avoid. This management pathology leads to unwanted changes in nature, a loss of ecological resilience, conservative management policies and loss of trust in management agencies.

Recent work reveals a way out of this pathology in large, regional-scale systems. These systems move through periods of surprise, crisis, and reformation (Gunderson, et al. 1995). Managers are surprised when the inadequacies of many, if not most, management policies are revealed by ecosystem dynamics. A crisis occurs when it becomes unambiguously clear that existing policies caused this surprise. The crisis is followed by periods of denial, resistance and often, finally, by a period of reformation, during which new policies are developed and implemented. It is during these periods of crisis, that institutions and the connections between them are most open to dramatic

transformation. This ability to transform and survive requires that the resource system have sufficient resilience to permit the experimental development of new management policies.

1.1.1 What is Resilience?

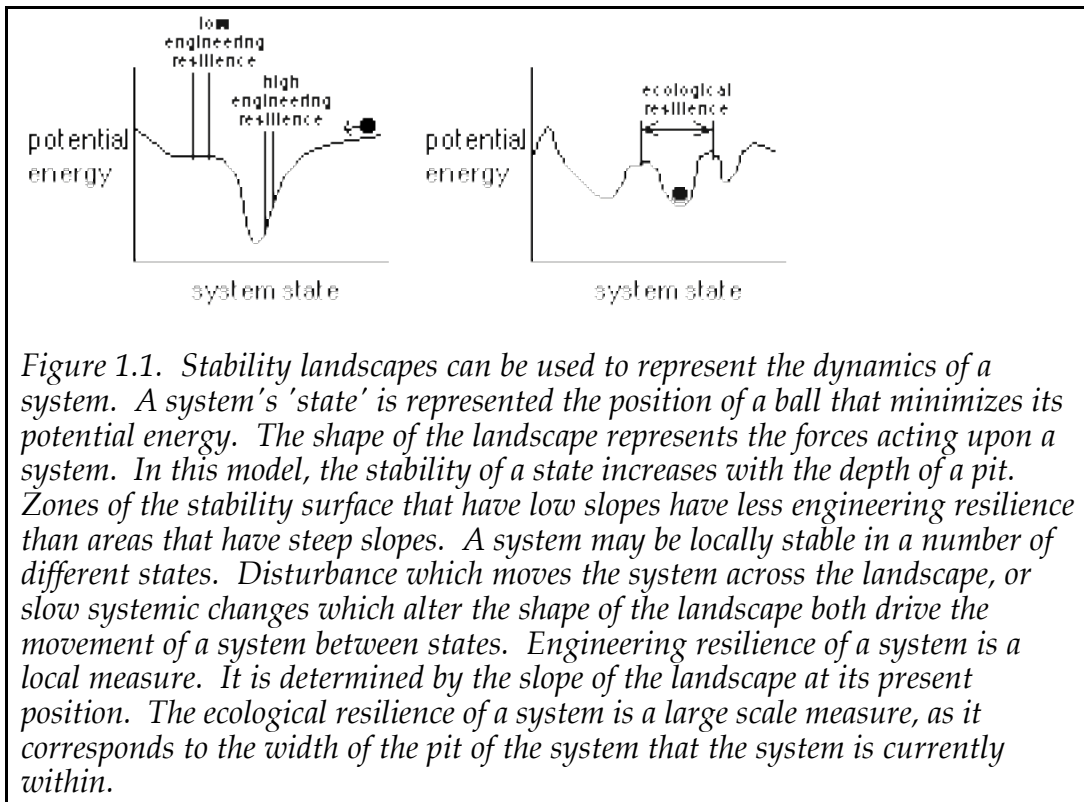
Resilience has been defined in two different ways in the ecological literature, each reflecting different aspects of stability. One definition focuses on efficiency, constancy and predictability - all attributes of engineers' desire for fail-safe design. The other focuses on persistence, change and unpredictability - all attributes embraced and celebrated by evolutionary biologists and by resource managers who search for safe-fail designs. Holling (1973) first emphasized these different aspects of stability to draw attention to the tensions between efficiency and persistence, between constancy and change, and between predictability and unpredictability.

The more common definition, which we term engineering resilience (Holling 1996), considers ecological systems to exist close to a stable steady state. Resilience is the ability to return to the steady state following a perturbation (Pimm, 1984; O'Neill et al., 1986; Tilman et al., 1994). This idea of disturbance away from and return to a stable state is also at the center of economic theory (Varian 1992, Kamien and Schwartz 1991).

The second definition, which we term ecological resilience (Walker et al., 1969; Holling 1996), emphasizes conditions far from any stable steady-state, where instabilities can flip a system into another regime of behavior - i.e. to another stability domain (Holling, 1973). In this case resilience is measured by the magnitude of disturbance that can be absorbed before the system redefines its structure by changing the variables and processes that control behavior.

The differences between these two aspects of stability - essentially between a focus on maintaining efficiency of function (engineering resilience) vs. a focus on maintaining existence of function (ecological resilience) - are so fundamental that they can become alternative paradigms whose devotees reflect traditions of a discipline or of an attitude more than a reality of nature. Those using the concept of engineering resilience tend to explore system behavior near a known stable state, while those examining ecological resilience tend to search for alternative stable states, and the properties of the boundaries between states.

Those who explore engineering resilience and the near equilibrium behavior of ecosystems operate in the primarily deductive tradition of mathematical theory (e.g. Pimm, 1984) that imagine simplified, untouched ecological systems, or they draw upon the traditions of engineering, that are motivated by the need to design systems with a single operating objective (Waide and Webster, 1976; DeAngelis, 1980; O'Neill et al., 1986). These approaches simplify the mathematics and accommodate the engineer's drive to develop optimal designs. However, there is an implicit assumption that ecosystems exhibit only one equilibrium steady-state or, if other operating states exist, that those states should be avoided (Figure 1.1).



On the other hand, those who emphasize ecological resilience come from traditions of applied mathematics and applied resource ecology at the scale of ecosystems - e.g. of the dynamics and management of fresh water systems (Fiering, 1982), of forests (Holling et al., 1977), of fisheries (Walters, 1986), of semi-arid grasslands (Walker et al., 1969) and of interacting populations in nature (Sinclair et al., 1990; Dublin et al., 1990). Because these studies are rooted in inductive rather than deductive theory formation and in experience with the impacts of large scale management actions, it becomes clear that the variability of critical variables forms and maintains the stability landscape. When this variability is reduced, an ecosystem can flip from one organization to another (Figure 1.1).

In economics, there has also been a focus on single stable state. The history of economics has been to rapidly move from establishing the existence of a general equilibrium to issues of equilibrium uniqueness or stability. If multiple equilibria are shown to theoretically exist, then the challenge that is usually taken up is to theoretically eliminate stable states by proposing individuals' strategic expectations and predetermined normative and social institutions. This approach does not examine or explain the conditions that can cause a system to move from one stability domain to another. However, the identification of multi-stable states due to path dependency (Arthur et al., 1987), chreodic development (Clark and Juma 1987) and production non-convexities such as increasing returns to scale (David 1985) has reintroduced multiple stable-states to economics.

The existence, or at least importance, of multiple or a single stable state determines the appropriateness of an engineering or ecological approach to resilience. If it is assumed that only one stable state exists or can be designed to exist, then the only possible definition and measures for resilience are near equilibrium ones - such as characteristic return time. And that is certainly consistent with the engineer's desires to make things work, not to intentionally make things that break down or suddenly shift their behavior. But nature and human society are different.

1.2. Why Study Resilience?

Complex resource systems are organized from the interactions of a set of ecological, social and economic systems across a range of scales. Resilience is central to understanding the dynamics of these systems and their vulnerability to various shocks and disruptions. Resilience measures the strength of mutual reinforcement between processes. Both the ability of a system to persist despite disruptions and the ability to regenerate and maintain existing organization. Resilience allows a system to withstand the failure of management actions. Management is necessarily based upon incomplete understanding, and therefore ecological resilience allows people in resource systems to affordably learn and change.

The importance of the role of resilience in ecosystems, flexibility of institutions and incentives in economies emerged in a sequence of meetings held on the island of Askö in the Swedish archipelago. Sponsored by the Beijer Institute of the Swedish Academy of Sciences, these meetings brought together economists and natural scientists to explore similarities and differences in views and experiences of change. Their conclusions were that economic growth is not inherently good, nor inherently bad, but that economic growth cannot in the long term compensate for declines in environmental quality. They also concluded that the growing scale of human activities is encountering the limits of nature to sustain that expansion (Folke and Berkes 1998; Arrow et al. 1995).

The familiar responses to these issues are often flawed, because the theories of change underlying them are inadequate. The stereotypical economist might say 'get the prices right' (i.e. ensure that prices internalize significant environmental externalities), without recognizing that price systems require a stable context where social and ecosystem processes behave 'nicely' in a mathematical sense (i.e. are continuous and convex). The stereotypical ecologist might say 'get the indicators right' without recognizing the surprises that nature and people inexorably and continuously generate. The stereotypical engineer might say 'get the technological control right and we can eliminate those surprises' without recognizing the limits to knowledge and control imposed by the inherent uncertainty and unpredictability of the ever-evolving interaction of people and nature.

Although based on bad or insufficient theory, such simple prescriptions are attractive because they seem to replace inherent uncertainty with the spurious certainty of ideology, of precise numbers or of action. The theories implicit in these examples ignore multi-stable states. They ignore the possibility

that the slow erosion of key controlling processes can cause an ecosystem or economy to abruptly flip into a different state that might effectively be irreversible. In an ecosystem, this might be caused by the gradual loss of a species in a keystone set that together determine structure and behavior over specific ranges of scale. In a resource based economy it might be implementation of maximum sustained yield policies that reduce spatial diversity, evolve ever narrower economic dependencies and develop more rigid organizations. In an economy, it might be caused by the channeling of loans through personal networks, allowing bad loans to accumulate to such a point that they cause an entire banking and finance system to collapse -- such as the recent crisis in southeastern Asia.

It increasingly appears that effective and sustainable development of technology, institutions, economies and ecosystems requires ways to deal not only with near equilibrium efficiency but with the reality of more than one possible equilibrium. If there are multiple equilibria, in which direction should the finger on the invisible hand of Adam Smith point? If there is more than one objective function, where does the engineer search for optimal designs? In such a context, a near equilibrium approach is myopic. Attention should shift to determining the constructive role of instability in maintaining diversity and persistence, and to management designs that maintain ecosystem function despite unexpected disturbances. Such designs maintain or expand the ecological resilience of those ecological "services" that invisibly provide the foundations for sustaining economic activity and human society.

The goal of this volume is to begin to understand how the properties of ecological resilience and human adaptability interact in complex, large systems (regional size). To begin a foundation for this volume, we initially review other key properties of complex adaptive systems that contribute to resilience.

1.3 Properties Of Complex Adaptive Systems

We propose that the behavior of complex adaptive systems depends upon four key properties: ecological resilience, complexity, self-organization and order. As discussed above, resilience is the extent to which a system can withstand disruption before shifting into another state. Complexity is the variety of structures, and processes that occur within a system. Self-organization is the ability of these structures and processes to mutually interact to reinforce and sustain each other. The process of self-organization produces order from disorder, but the interaction of processes across scales also destroys, and reconfigures ecological organization producing complex ecological dynamics. The next three sections elaborate upon the role these properties play in complex systems, and how these other properties contribute and interact with resilience.

1.3.1. Diversity and Stability

The relationship between biological diversity and ecological stability has been an ongoing debate in ecology since the time of Darwin (1860; Elton 1958; May 1973; Tilman 1994, 1996). The question is whether an ecosystem that

includes more species is more stable than one that includes fewer species?

Tilman (1994, 1996) demonstrated that an increase in species number increases the efficiency and stability of some ecosystem functions, but decreases the stability of the populations of the species at least over ecologically brief periods. While this work is important and interesting, it focuses upon how an ecosystem behaves near some steady state. As we discussed above, we feel it is important to discover the role of ecological diversity over a much broader range of variations. This is where the relationship between diversity and resilience has been poorly developed.

When grappling with this broader relationship between diversity and resilience two hypotheses are commonly discussed: Ehrlich's (1991) 'rivet' hypothesis and Walker's (1992) driver and passengers hypothesis. The rivet hypothesis proposes that there is little change in ecosystem function as species are added or lost, until a threshold is reached. At that threshold the addition or removal a single species leads to system reorganization. The 'rivet' hypothesis assumes that species have overlapping roles, and that as species are lost the ecological resilience of the system is decreased, and then overcome entirely. Walker proposes that species can be divided into 'functional groups' or 'guilds', which are groups of species that act in an ecologically similar way. Walker proposes that these groups can be divided into 'drivers' and 'passengers'. Drivers are 'keystone' species that control the future of an ecosystem, while the passengers live in but do not significantly alter their ecosystem. However, as conditions change, endogenously or exogenously, species shift roles. Removing passengers has little effect, while removing drivers can have a large impact. Ecological resilience resides both in the diversity of the drivers, and in the number of passengers who are potential drivers. These two hypotheses provide a start, but richer models of ecological complexity are needed that better incorporate ecological processes, dynamics and scale.

Ecosystems are resilient when ecological interactions reinforce one another, and dampen disruptions. Such situations may arise due to compensation when a species with an ecological function similar to another species increases in abundance as the other declines (Holling 1996), or as one species reduces the impact of a disruption on other species.

Theory, models and data suggest that a small number of keystone processes create discontinuous spatial and temporal patterns in ecosystems (Holling et al. 1996, Levin 1995) yet allow for great diversity of organisms. These keystone ecological processes produces a discontinuous distribution of structures in ecosystems, and these discontinuous structures generate discontinuous patterns in adult body masses of animals that inhabit landscapes (Holling 1992, Morton 1990). Consequently, while animals that function at the same scale are separated by functional specialization (e.g. insectivores, herbivores, arboreal frugivores, etc.), animals that function at different scales can utilize similar resources (e.g. shrews and anteaters are both insectivores but utilize insects at different scales). We propose that the resilience of ecological processes, and therefore of the ecosystems they maintain, depends upon the distribution of functional groups within and across scales (Peterson et al 1998).

Across-scale resilience is produced by the replication of process at

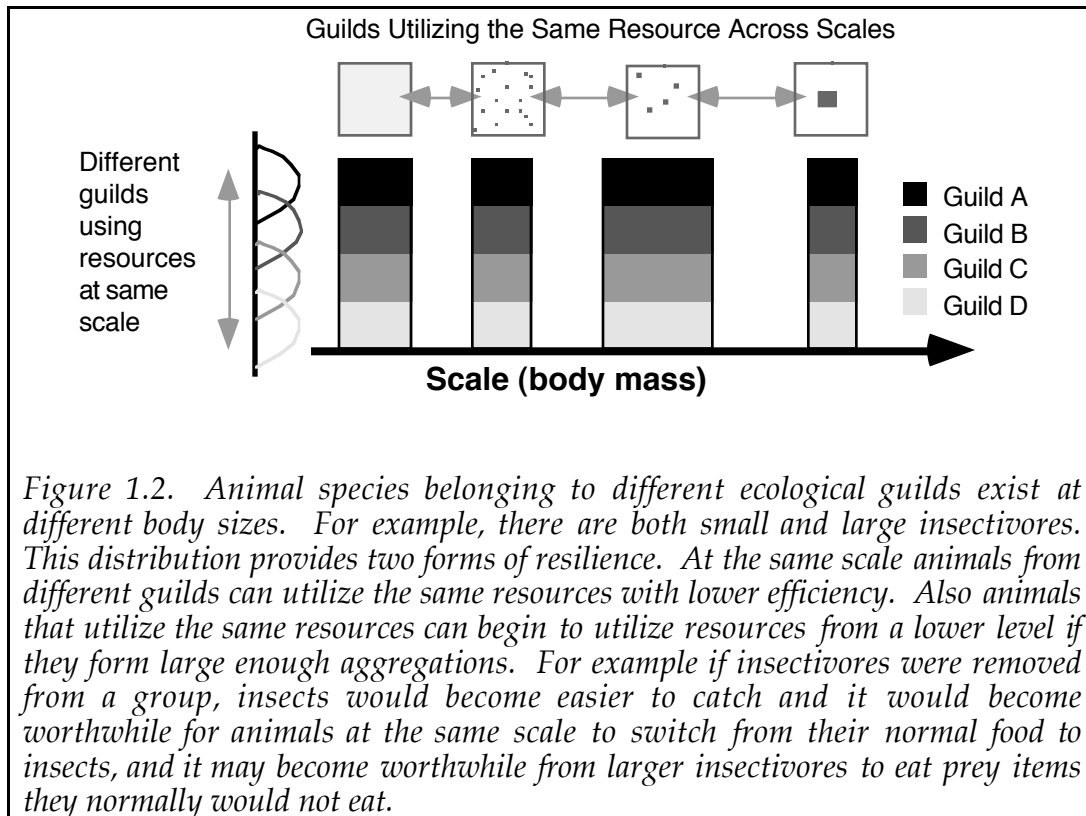
different scales. The apparent redundancy of similar function replicated at different scales adds resilience to an ecosystem, because disturbances are limited to specific scales functions that operate at other scales are able to persist.

Local processes such as competitive relationships certainly contribute to species differences among ecosystems. However, the structural differences between ecosystems from the tundra to the tropics are primarily produced by larger scale disturbance processes which are initiated locally and spread across landscapes. These contagious processes include abiotic processes, such as fire, storms, and floods, and zootic processes such as insect outbreaks, large mammal herbivory and habitat modification (Naiman, 1988; McNaughton, 1988; Pastor and Cohen 1996). These processes, interacting with topography and regional climate, form the ecosystem-specific structures that shape the morphology and diversity of animal communities. They also generate spatial and temporal variation which increases the diversity of plant species by periodically overriding the competitive dominance relations that occur locally (Holling, 1991). For example in the eastern boreal forest of Canada, fire and spruce budworm outbreaks kill large areas of forest. In interaction, with climate, existing vegetation, and each other these processes produce a mosaic of even aged forest stands in the landscape. Since the age a stand reaches before being destroyed is primarily determined by disturbance, and what species exist within the stand is influenced by landscape pattern - these disturbance processes also strongly control what exists within stands. Consequently, these disturbance processes strongly influence the distribution and type of resources that occur in eastern Canadian boreal forest across a broad range of ecological scales.

An ecosystem that has several scales of ecological structure allows members of multi-taxa food guilds to minimize competition by utilizing resources that are available at different scales (Figure 1.2). The replication of function across scales can be seen on Brazil's Maracá Island Ecological Reserve, where palm seeds are dispersed across a range of scales by a variety of species (Fragoso 1997). Seed dispensers range in size from small rodents, which typically disperse seeds within 5m of parent trees, to tapirs (*Tayassu tajacu*), which disperse seeds up to 2 km. Seed dispersal at multiple scales allows the palm population to persist despite a variety of disturbance processes occurring at different scales, because the trees are dispersed across the landscape at different scales.

Within-scale resilience complements cross-scale resilience. Within-scale resilience is produced by compensating overlap of ecological function between similar processes that occur at the same scales. For example, when a range of food resources are exploited by the set of foragers, rapid response to sudden increases or decreases in one type of food becomes possible and introduces strong negative feed-back regulation over a wide range of densities of the food items (Holling 1987). The consequence of all that variety is that the species combine to form an overlapping set of reinforcing influences that are less like the redundancy of engineered devices and more like portfolio diversity strategies of investors. The risks and benefits are spread widely to retain overall consistency in performance independent of wide fluctuations in the individual species. Functional diversity provides great robustness to the functioning of the process

and, as a consequence, great resilience to the system behavior. Moreover, this seems the way many biological processes are regulated- overlapping influences by multiple processes, each one of which is inefficient in its individual effect but together operating in a robust manner. For example, those are the features of the multiple mechanisms controlling body temperature regulation in endotherms, depth perception in animals with binocular vision and direction in bird migration.



Because of the ecological resilience produced by functional diversity and the non-linear way behavior suddenly flips from one ecological organization to another, gradual loss of species involved in maintaining ecological organization initially may have little immediate impact. As the loss of species continues, suddenly, different behavior would emerge more and more frequently in more and more places. To the observer, it would appear as if only the few remaining species were critical when in fact all add to the resilience. Although behavior would change suddenly, resilience measured as the size of stability domains (*sensu* Holling 1973), would gradually contract. The system, in gradually losing resilience, would become increasingly vulnerable to perturbations that earlier could be absorbed without change in function, pattern and control.

1.3.2 Cross-Scale Dynamics

In nature, different structures and processes dominate at different scales. For example, in the boreal forest, fresh needles cycle yearly, the crown of foliage cycles with a decadal period and trees, gaps and stands cycle at close to a century or longer periods. Ecological organization can be viewed as a hierarchy in which each hierarchical level has its own distinct spatial and temporal attributes. A critical feature of such hierarchies is the asymmetric interactions between levels (Allen and Starr 1982, O'Neill, et al. 1986). In particular, the larger, slower levels constrain the behavior of faster levels; that is, slower levels control faster ones. However, if that was the only asymmetry then hierarchies would be static structures and it would be impossible for organisms to exert control over slower environmental variables. However, these hierarchies are not static, but are transitory structures maintained by interaction across scales.

Birth, growth, death and renewal cycles (Figure 1.3), transform hierarchies from fixed static structures to dynamic adaptive entities whose levels are sensitive to small disturbances at the transition from growth to collapse (the omega phase), and the transition from reorganization to rapid growth (the alpha phase). During other times, the processes are stable and resilient. They constrain lower levels and are immune to the buzz of noise from small and faster processes. It is at the two phase transitions between gradual and rapid change that the large and slow entities become sensitive to change from the small and fast ones.

When the system is reaching the limits to its conservative growth, it becomes increasingly brittle and its accumulated capital is ready to fuel rapid structural changes. The system is very stable, but that stability derives from a web of interacting connections. When this tightly connected system is disrupted; a disruption can quickly spread, destabilizing an entire system. The specific nature and timing of the collapse-initiating disturbance determines, within some bounds, the future trajectory of the system. Therefore this brittle state presents the opportunity for a change at a small scale to cascade rapidly through a system and bring about its rapid transformation. This is the "revolt of the slave variable" (Diener and Poston 1984). Such a collapse can be initiated by either internal conditions (e.g. the amplification of internal oscillations) or external events (e.g. the amplification of an external disturbance). Internally induced brittleness (linked to over connected, and accumulated capital) provides the conditions for an externally triggered collapse.

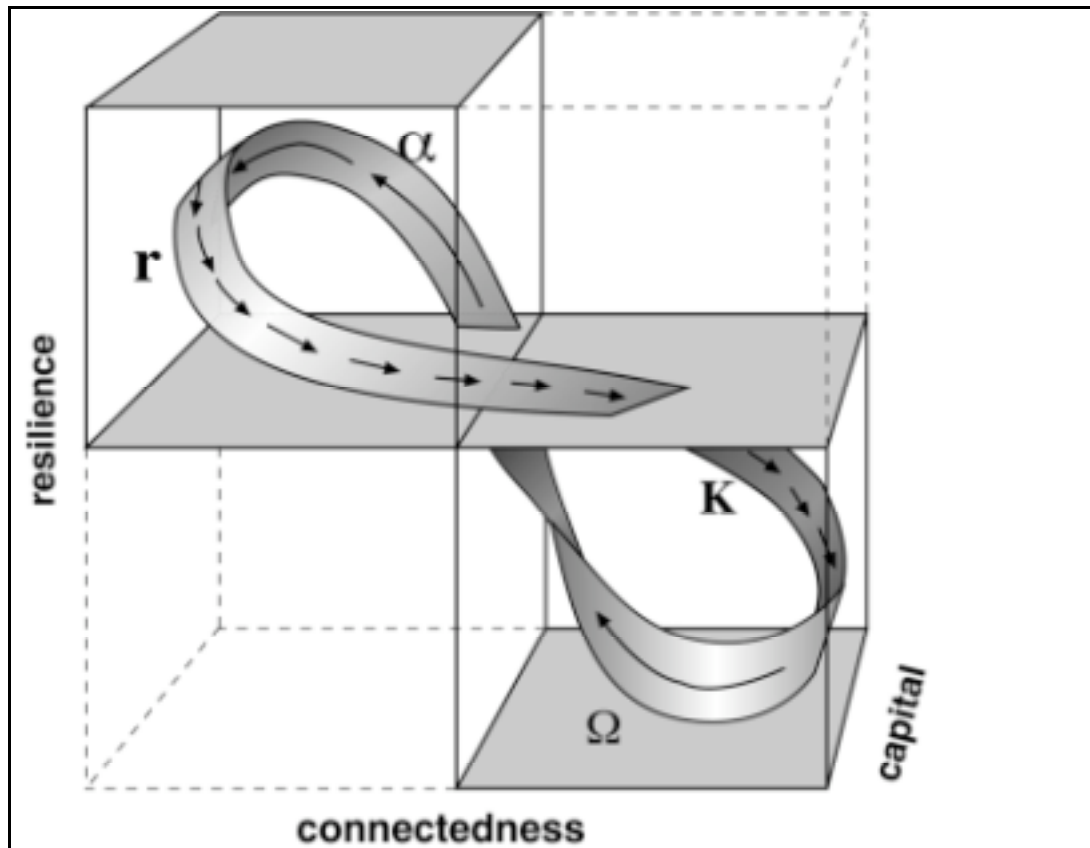


Figure 1.3 . Ecosystem dynamics, indicating transitions among ecosystem status (r, K, α, Ω) and the resilience of each . The arrows show the speed of that flow in the cycle, where arrows close to each other indicate a rapidly changing situation and arrows far from each other indicate a slowly changing situation. The cycle reflects changes in three attributes, (1) X axis: the degree of connectedness among variables and (2) Y axis: the resilience of the system (3) Z axis: the amount of accumulated capital (nutrients, carbon) stored in variables that are the dominant structuring variables at that moment the resilience of the system. The exit from the cycle indicated at the left of the figure indicates the stage where a state change is most likely into a less or more productive and organized system.

The second opportunity for small-scale processes to cause system change is during the transition from reorganization to exploitation, that is, from alpha to r. During this reorganization phase the system is in a state opposite to the conservation phase previously described. There is little local regulation and stability, so that the system can easily be moved from one state to another. Resources for growth are present, but they are disconnected from the processes that facilitate and control growth. In such a weakly connected state, a small scale change can nucleate a structure amidst a sea of chaos. This new structure can then use the available resources to grow explosively and to establish the exploitative path along which the system develops. As in Waddington's chreodic

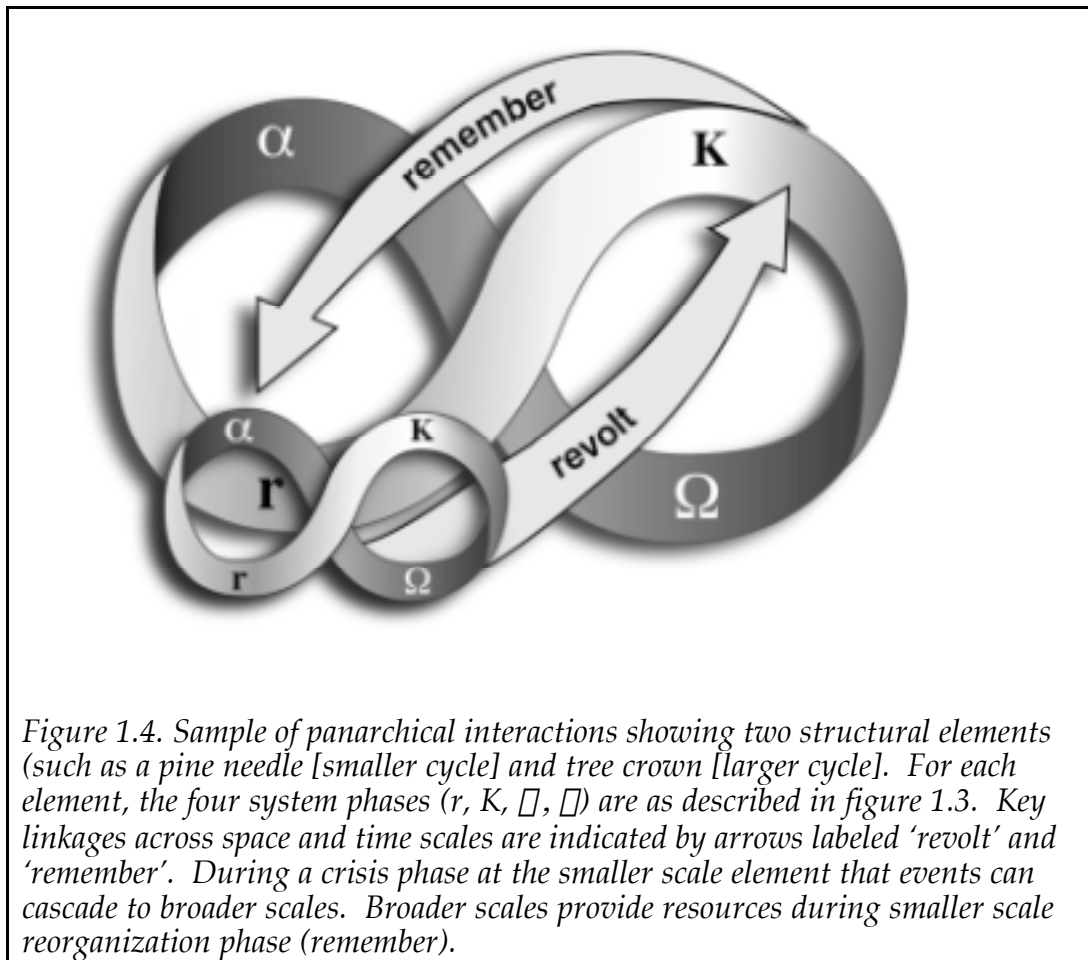
development model, there is not a stable point; rather there is a stable trajectory that progressively reinforces itself (Hodgson 1993). In Waddington's (1969) words, "the system is not homeostatic (around a point), it is homeorhetic (around a path)". This transition occurs as small scale changes sow seeds of order in the larger and slower chaos within which they are embedded. The budworm example illustrates these changes where transient bottom-up asymmetry provides an opening for evolutionary change. That is, the previous system pattern may reassert itself, or the system may reorganize itself into a novel structure.

As systems go through phases of the adaptive cycle, resilience changes. This is presented as a third dimension in Figure 1.3. When the system is reaching the limits to its conservative growth (K phase), it becomes increasingly brittle and its accumulated capital is ready to fuel rapid structural changes. The system is very stable, but that stability is self-maintaining and brittle leaving the system vulnerable to novelty. A small disturbance can push it out of that stable domain into catastrophe; hence its resilience is relatively low. The nature and timing of the collapse-initiating disturbance determines, within limits defined by the nature of lower and higher hierarchical levels the future trajectory of the system. During reorganization (alpha phase) a system has greater resilience but little stability. Fluctuations in large scale processes, such as climate, or in small scale processes, such as a seed bank, can result in a system establishing different organizations.

1.3.3 Panarchy

The accumulating body of evidence from studies of ecosystems indicates that processes and structures often are discontinuous, and ecosystems can exhibit multiple stable states. The four phase cycle of adaptive renewal captures many of these dynamics for ecological systems (Figure 1.3). However, that model is appropriate for structures within a specific range of scales, and those dynamics occur at multiple hierarchical scales or levels. By considering the dynamics of adaptive cycles interacting across scale, we have developed a model of cross-scale ecological organization that we term describe as 'panarchy'.

Panarchy is used to describe the dynamic nature of interacting hierarchies. We prefer this term over hierarchy, because it emphasizes the dynamic and transient nature of connections between scales. Different systems exhibit the birth, growth, death and renewal phases of the adaptive cycle at different specific scale ranges (Figure 1.3). As in a conventional hierarchy, the processes within a level are stable and self-maintaining, constraining smaller and faster processes, while benign immune to their fast fluctuations. However, the panarchy model transforms hierarchies from fixed static structures to dynamic adaptive entities whose levels are sensitive to small disturbances at the transition from growth to collapse (the omega phase), and the transition from reorganization to rapid growth (the alpha phase). It emphasizes that the 'creative destruction' that follows 'revolt' and the 'remembrance' that shapes reorganization are the produces of cross-scale interactions (Figure 1.4).



Tests of resilience are from the "Revolt" event. Revolts are enabled by the interaction across scales of slow and fast variables. Resilience shrinks as slow accumulation of capital over time and an increase in connectivity over space makes the system vulnerable to the destabilizing effect of fast variables that trigger a cascade of creative destruction. This has been described as the "revolt of the slave variable". Collapse can be initiated by either internal conditions or external events, but typically it is internally induced brittleness (linked to over connected, and accumulated capital) that sets the conditions for collapse which coincides with a proximal triggering event associated with larger scale variation (i.e. external events).

Resilience is reestablished by the "Remember" process that connects the present to the past (e.g. accumulated seed banks) and the local to the distant (in-dispersal of propagules). It involves processes of regeneration and renewal. In social systems, examples of these connections include drawing upon and utilizing social capital, traditional knowledge, and wisdom. The remember process is also an opportunity for small scale processes to cause system change during the

transition from reorganization to exploitation, that is, from alpha to r. During this reorganization phase the system is in a state opposite to the conservation phase. There is little local regulation and stability, so that the system can easily be moved from one state to another. Resources for growth are present, but they are disconnected from the processes that facilitate and control growth. In such a weakly connected state, a small scale change can nucleate a structure amidst the sea of disorder. This structure can then use the available resources to grow explosively and to establish the exploitative path along which the system develops and then locks into. This transition occurs as small scale changes sow seeds of order in the larger and slower chaos within which they are embedded. The transient but critically important bottom-up asymmetry provides an opening for evolutionary change. That is, the previous system pattern may reassert itself, or the system may reorganize itself into a novel structure.

In this section, we have reviewed the theoretical and empirical foundations for understanding resilience in complex, adaptive systems. That foundation will be examined in the remaining chapters of this volume. To provide some focus for such evaluations, we develop a set of propositions.

1.4 Propositions

A theoretical review of the ecological processes organizing large scale ecosystems leads to a number of propositions. Because these propositions are largely based upon ecological literature, they may be inappropriate in other disciplinary areas. For this reason we offer them provisionally, so that their examination and testing focus the following discussion. Our intent is to provide a framework for subsequent chapters to explore, refine and reject these constructs as they apply to a wide variety of large scale, ecological systems. In this spirit we pose the following propositions:

• **The organization of regional resource systems emerges from the interaction of a few variables**

The essential structure and dynamics of complex systems are produced by the interaction of at least three and no more than six variables that operate at different spatial and temporal by approximately an order of magnitude.

• **Complex systems have multiple stable states.**

Complex systems can exhibit alternative stable organizations. Transitions between different organizations are due to changes in the interaction of structuring variables. Change often occurs when gradual change in a slow variable alters the interactions among faster variables.

• **Resilience derives from functional reinforcement across scales and functional overlap within scales.**

Resilience derives from both a duplication of function across a range of spatial and temporal scales, and from a diversity of different functions operating within each scale.

• **Vulnerability increases as sources of novelty are eliminated and as functional diversity and as cross-scale functional replication are reduced.**

Diminished sources of novelty reduce the ability of a system to recover from disturbances. The elimination of structuring species or processes can cause an ecosystem to reorganize. A reduction in functional diversity and duplication of functions reduces the ability of a system to persist.

1.5 Evaluation of Propositions In Large Scale Ecosystems

These propositions are evaluated in the case studies presented in this book. The book is divided into three parts: a theoretical introduction, case studies and synthesis. The theoretical introduction is provided by this chapter and the next chapter, which uses a set of mathematical metaphors to describe and deepen our understanding of the concepts of resilience. The second, and largest part of this volume, is a series of case studies that explore the biophysical dimensions of resilience, and evaluate the propositions described above. These case studies review resilience in both terrestrial and aquatic systems. The terrestrial systems include boreal forest, tropical rainforest, tropical dry forests, semi-arid savanna, and tropical agro-ecosystems. Aquatic ecosystems considered include coral reefs, freshwater lakes, wetlands, and inland seas (specifically the Baltic Sea). The book concludes with a synthesis section, revisiting these propositions in light of the case studies.

1.6 Literature Cited

- Allen, C. R., Forays, E. and C.S. Holling, C.S. (1995). Ecosystem disturbance and community transformation: gateway for invaders, exit for the endangered. *Ecosystems*. 3:
- Allen, T. F. H. and Starr, T.B. (1982). *Hierarchy: Perspectives for Ecological Complexity*. The University of Chicago Press, Chicago, IL: 310 pages.
- Arthur, W.B., Ermoliev, Y.M. and Kaniovski, Y.M. 1987. Path-dependent processes and the emergence of macro-structure. *European J. of Operational Research*; 30, 294-303.
- Clark, N. and Juma, C. 1987 *Long-run economics: an evolutionary approach to economics growth*. Pinter, London: 206 pages.
- Clark, W. C., Jones, D.D. and Holling, C.S. 1979. Lessons for ecological policy design: a case study of ecosystem management. *Ecological Modeling*; 7,1-53.
- Darwin Charles. 1860. *On the origin of species by means of natural selection, or, The preservation of favoured races in the struggle for life*. 5Th ed. London, J. Murray. 502 pages.
- DeAngelis, D. L. 1980. Energy flow, nutrient cycling and ecosystem resilience. *Ecology* ; 61, 764-771.
- Diener, M., and Poston, T. 1984. On the perfect delay convention or the revolt of the slaved variables. In Haken, H. (Ed) *Chaos and Order in Nature*: 249-268, Springer-Verlag, Berlin.
- Dublin, H. T., Sinclair, A.R.E. and McGlade, J. 1990. Elephants and fire as causes of

- multiple stable states in the Serengeti-mara woodlands. *J. of Animal Ecology*; 59,1147-1164.
- Ehrlich, P.R. 1991. Population diversity and the future of ecosystems *Science*; 254, 175.
- Elton, C.S. 1958. *The ecology of invasions by animals and plants*. Methuen, London: 181 pages.
- Fiering, M.B. 1982. Alternative indices of resilience. *Water Resources Research*; 18, 33-39.
- Folke, C. and F. Berkes. 1998. *Linking Ecological and Social Systems*. Cambridge Press, Cambridge.
- Fragoso, J. M. V. 1997. Tapir-generated seed shadows: scale-dependent patchiness in the Amazon rain forest. *Journal of Ecology* 85:519-529.
- Gunderson, L. H., Holling, C.S. and Light, S. *Barriers and Bridges to Renewal of Ecosystems and Institutions*. New York: Columbia University Press: 593 pages.
- Hodgson, G.M. 1993. *Economics and Evolution: Bringing Life Back into Economics*. University of Michigan Press, Ann Arbor: 381 pages.
- Holling, C. S. 1973. Resilience and stability of ecological systems. *Ann. Rev. of Ecol. and System.*; 4,1-23.
- Holling, C. S. 1986. Resilience of ecosystems; local surprise and global change. In Clark, W.C. and Munn, R.E. (Eds) *Sustainable Development of the Biosphere*: 292-317. Cambridge: Cambridge University Press.
- Holling, C. S. 1991. The role of forest insects in structuring the boreal landscape. In Shugart, H.H., Leemans, R. and Bonan, G.B. (eds): *A Systems Analysis of the Global Boreal Forest.*: 6, 170-191. Cambridge University Press, Cambridge.
- Holling, C. S. 1992. Cross-scale morphology, geometry and dynamics of ecosystems. *Ecol. Mono.*; 62 (4), 447-502.
- Holling, C. S., Jones, D.D. and Clark, W.C. 1977. Ecological policy design: a case study of forest and pest management. In Norton, G.A. and Holling, C.S. (Eds). *Proceedings of a Conference on Pest Management*, October 1976, IIASA CP-77-6, 13-90, Laxenburg, Austria.
- Holling, C.S., Peterson, G., Marples, P., Sendzimir, J., Redford, K., Gunderson, L. and Lambert, D. 1996. Self organization in ecosystems: lumpy geometries, periodicities and morphologies. In, Walker, B. and Steffen, W. (Eds) *Global Change in Terrestrial Ecosystems*. 346-384. Cambridge University Press, Cambridge.
- Jansson, B.-O. and Velner, H. The Baltic; a sea of surprises. In Gunderson, L. H., Holling, C.S. and Light, S. (Eds). *Barriers and Bridges to Renewal of Ecosystems and Institutions*. Pp.292-372. New York: Columbia University Press.
- Kamien, M.I. and Schwartz, N.L. 1991. *Dynamic Optimization: The Calculus of Variations and Optimal Control in Economics and Management*. North-Holland, Amsterdam. Elsevier Science: 377 pages.
- Lee, K. 1993. *Compass and Gyroscope*. Island Press, Washington DC: 243 pages.
- Levin, S. 1995. *Biodiversity: Interfacing Populations and Ecosystems*. Kyoto

- University Press, Kyoto. 294 pages.
- Light, S. S., Gunderson, L.H. and Holling, C.S. 1995. The Everglades; Evolution of Management in a Turbulent Environment. *In Barriers and Bridges to Renewal of Ecosystems and Institutions*. 103-168. New York: Columbia University Press.
- Ludwig, D., Hilborn, R. and Walters, C. 1993. Uncertainty, resource exploitation, and conservation: Lessons from history. *Science* ; 260, 17 & 36.
- May, R.M. (1973). *Stability and Complexity in Model Ecosystems*. Princeton University Press, Princeton, N.J: 235 pages.
- McNaughton, S. J., Ruess, R.W. and Seagle, S.W. 1988. Large mammals and process dynamics in African ecosystems. *BioScience* ;38, 794-800.
- Morris, R. F. 1963. The dynamics of epidemic spruce budworm populations. *Mem. of the Ent. Soc. of Canada*; 21, 332.
- O'Neill, R. V., DeAngelis, D.L., Waide, J.B. and T. F. H. Allen. 1986. *A Hierarchical Concept of Ecosystems*. Princeton: Princeton University Press, Princeton.
- Peterson, G. D., C. R. Allen and C. S. Holling. 1998. Ecological resilience, biodiversity and scale. *Ecosystems* 1:6-18.
- Pastor, J. and Cohen, Y. 1996. Herbivores, plant populations and the cycling of nutrients in ecosystems. *American Naturalist*
- Sinclair, A. R. E., Olsen, P.D. and T. D. Redhead, T.D. (1990). Can predators regulate small mammal populations? Evidence from house mouse outbreaks in Australia. *Oikos*; 59:382-392.
- Smith, T. M. & D. L. Urban, D.L. (1988). Scale and the resolution of forest structural pattern. *Vegetatio*; 74:143-150.
- Tilman David, John A. Downing. 1994. Biodiversity and stability in grasslands. *Nature* 367:363-365.
- Tilman, D. 1996. Biodiversity: Population versus ecosystem stability. *Ecology* 77:350-363.
- Varian, H.R., 1992. *Microeconomic analysis*. W.W. Norton & Company, New York and London: 506 pages.
- Volkman, J. and W. E. McConnaha. 1993. Through a glass darkly: Columbia River salmon, the Endangered Species Act, and adaptive management. *Environmental Law* 23:1249-1272
- Waddington, C.H., 1969. The theory of evolution today. In: A. Koestler and J.R. Smythies (Editors), *Beyond reductionism: new perspectives in the life sciences*. Hutchinson, London, pp. 357-374.
- Waide, J. B. and J. R. Webster. 1976. Engineering systems analysis: applicability to ecosystems. Volume IV, pp. 329-371 in *Systems Analysis and Simulation in Ecology*, B. C. Patten, ed. New York: Academic Press.
- Walker, B. 1995. Conserving Biological Diversity through Ecosystem Resilience. *Cons. Biol.* 9 (4):747-752.
- Walker, B. H., Ludwig, D., Holling, C. S., and R.M. Peterman. 1969. Stability of semi-arid savanna grazing systems. *Ecology* 69, 473-498.
- Walker, B. H. 1992. Biological diversity and ecological redundancy. *Cons. Biol.* 6 18-23.
- Walters, C. J. 1986. *Adaptive Management of Renewable Resources*. New York: McGraw Hill. 374 pages.